High current coated conductors based on IBAD MgO and PLD YBCO

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One of our plans for this year was to identify and attempt to overcome limitations to thick film J_c

- Approach the drop in J_c with thickness as though it is a materials-processing issue, and not intrinsic. At a particular thickness, maximize J_c through a comprehensive process optimization. *Goal: Reproducible achievement of I_cs over 400 A/cm-width at a film thickness of ≤ 1.5 μm.*

  - Goal was met by optimizing the buffer layer deposition process.
  - Also developed a simple model for J_c dependence on thickness.
  - Tested one prediction of model, significantly increasing I_c beyond stated goal.

Process optimization focused on the laser-deposited $SrTiO_3$ buffer layer we use for IBAD MgO

- Changed to $SrTiO_3$ from $SrRuO_3$ last year.
- Initially used "standard" deposition conditions.
- Determined effect of buffer thickness on J_c (similar to CeO_2 on IBAD YSZ).
- Discovered an unexpected dependence on deposition temperature.

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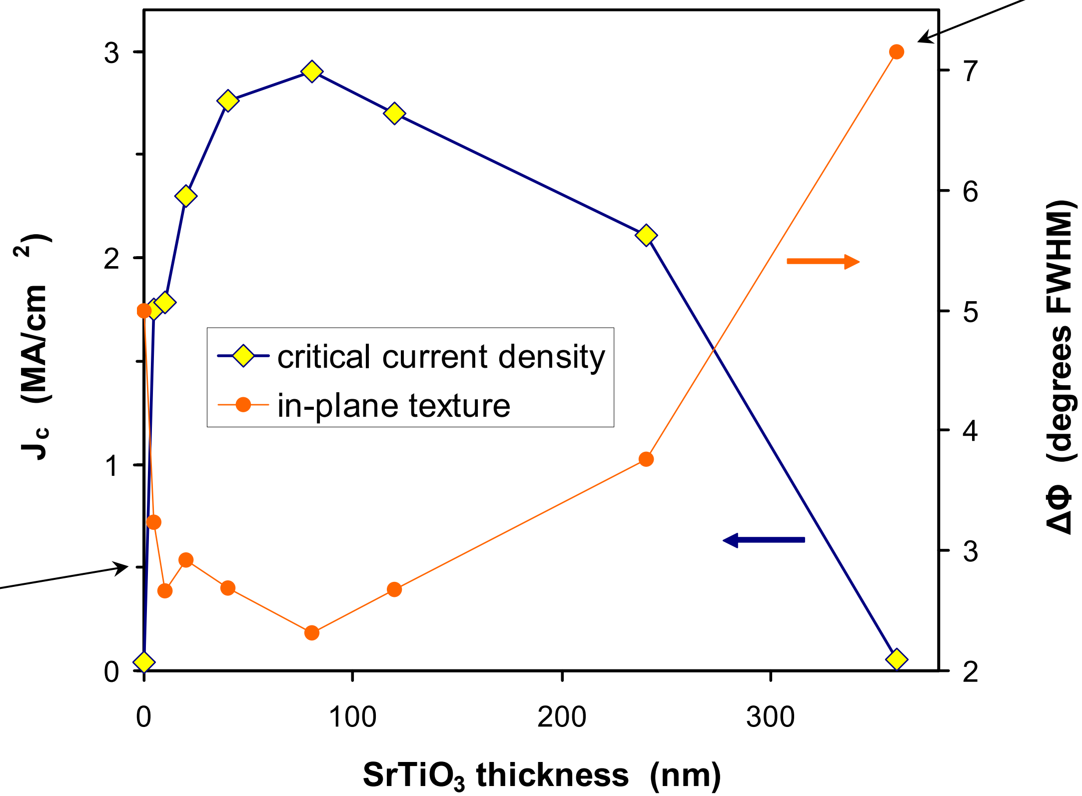
Optimum $SrTiO_3$ thickness is 40-120 nm

1.7 μm thick YBCO films on IBAD MgO

At 20 nm texture is OK.

Is diffusion of substrate elements responsible for lower J_c here?



At 360 nm $SrTiO_3$ is rough, resulting in poor YBCO texture

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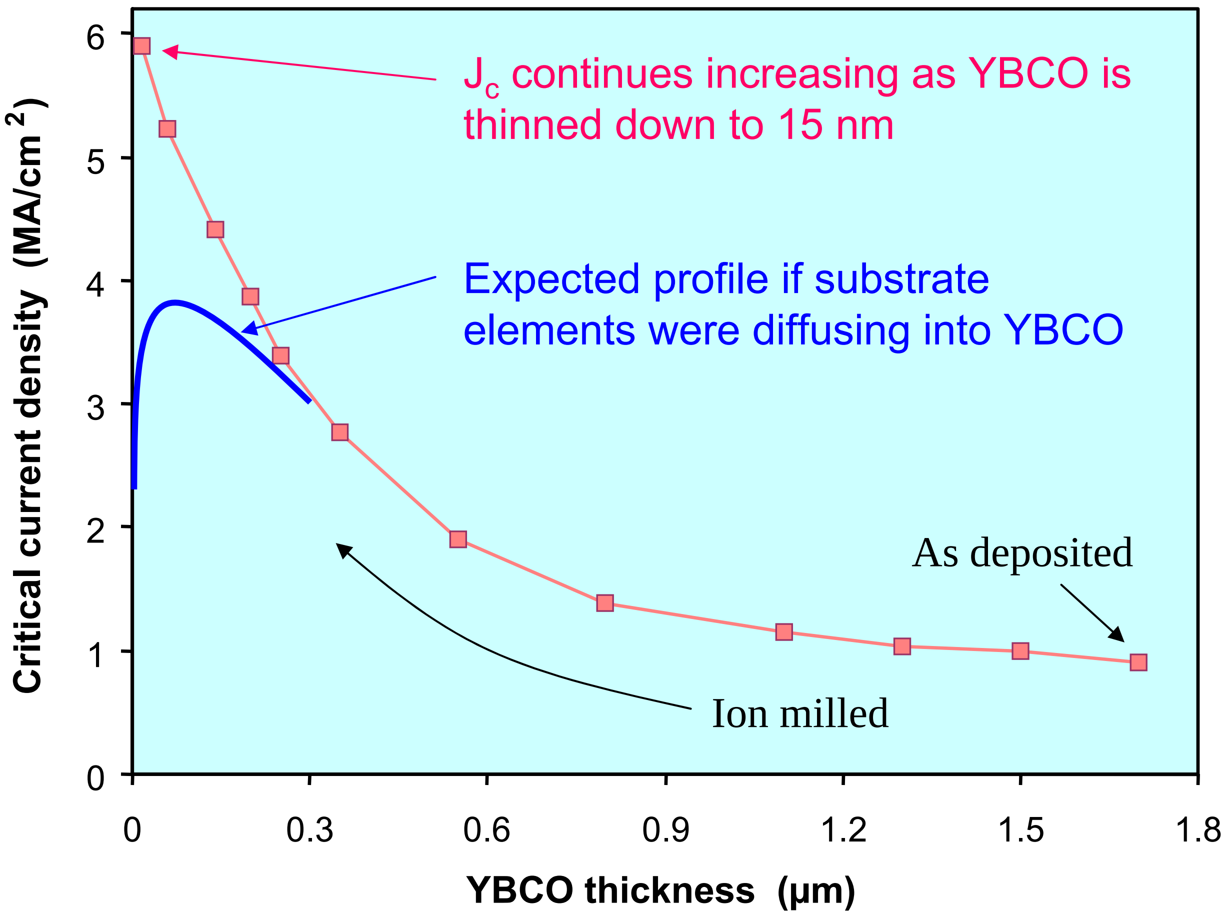
Ion milling reveals no diffusion problem, even for very thin $SrTiO_3$ (20 nm in this case).



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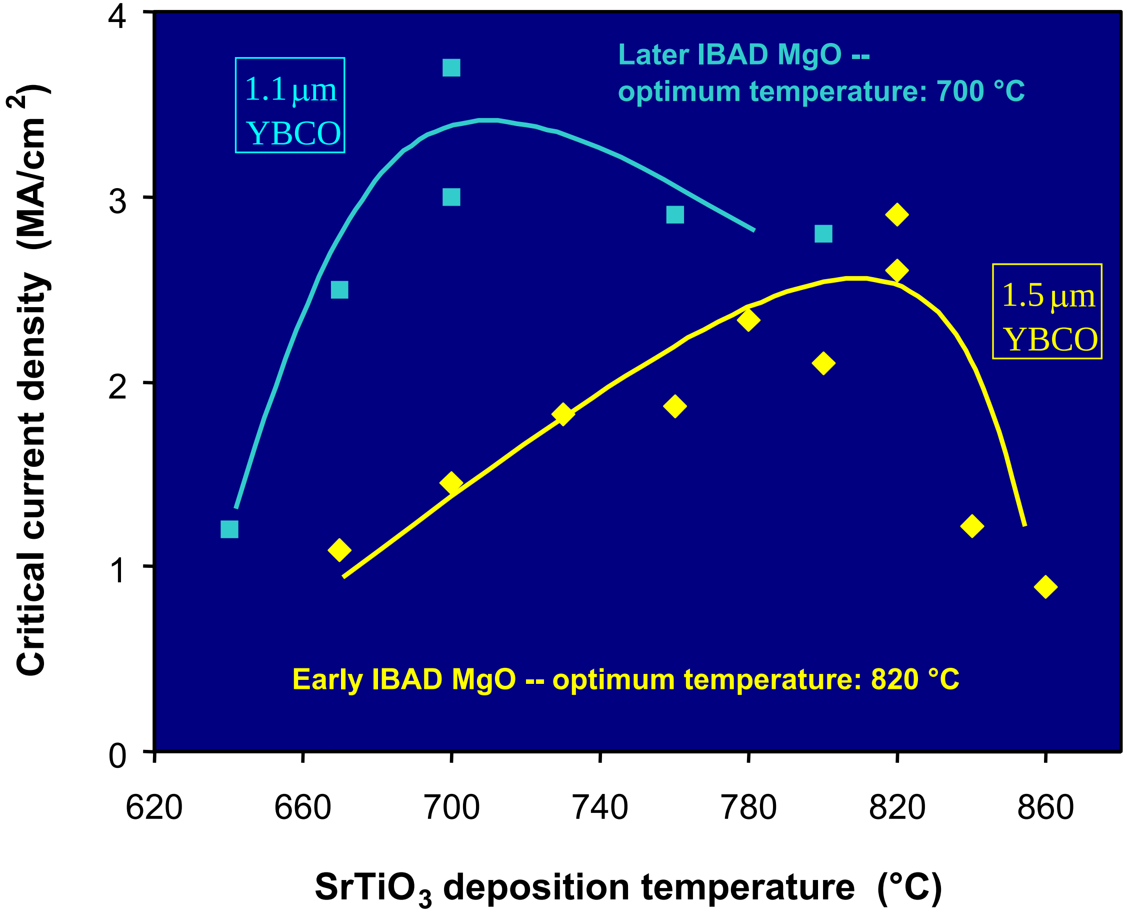
Optimum $SrTiO_3$ deposition temperature can vary for different IBAD MgO runs, but peak J_c values are similar

- YBCO texture is 2.4 – 3.6° FWHM in-plane, and is unaffected by $SrTiO_3$ deposition temperature
- YBCO deposition temperature is 760°C for all samples.



TEM analysis revealed thickness differences in the oxide layer stack but not why the optimum $SrTiO_3$ temperature is different

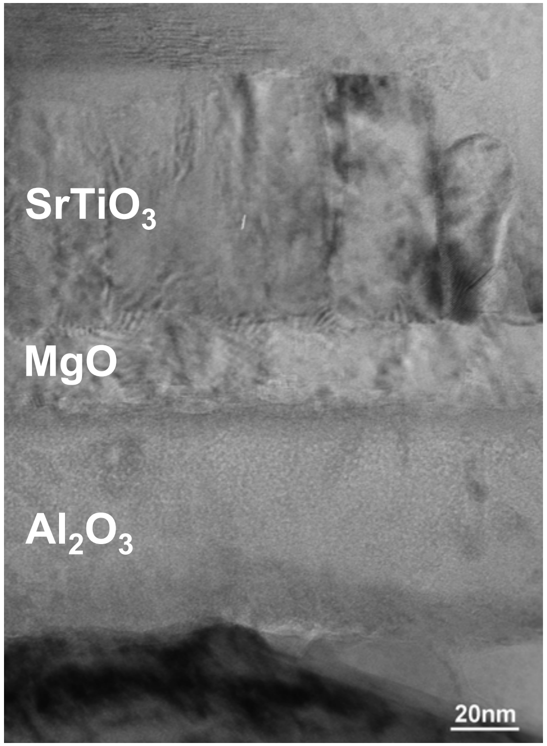
Early: T_{opt} = 820°C

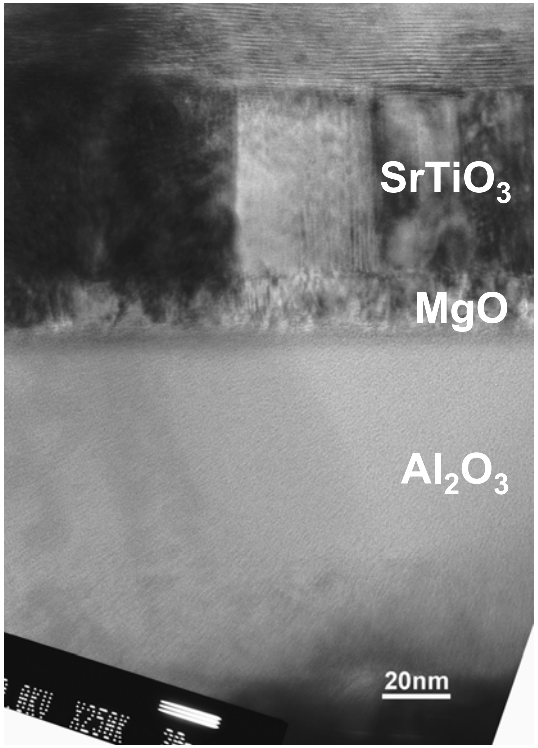
Later: T_{opt} = 700°C

72 nm

27 nm

68 nm





55 nm

19 nm

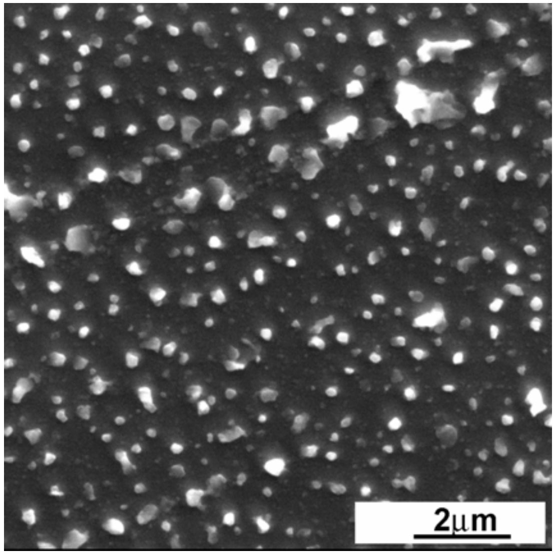
100 nm

In all cases, however, the highest J_c results from the $SrTiO_3$ deposition temperature that yields the smoothest surface

SEMs show fewer $SrTiO_3$ outgrowths on the buffer layer surface at the optimum deposition temperature

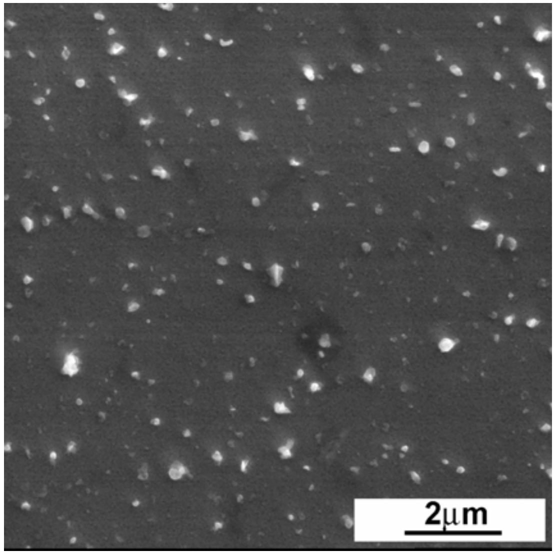
T_{dep}: 670°C

J_c: 1.1 MA/cm^2



T_{dep}: 820°C

J_c: 3.0 MA/cm^2



H. Wang, *et al.*, J. Mater. Res. **19**, 1869 (2004).

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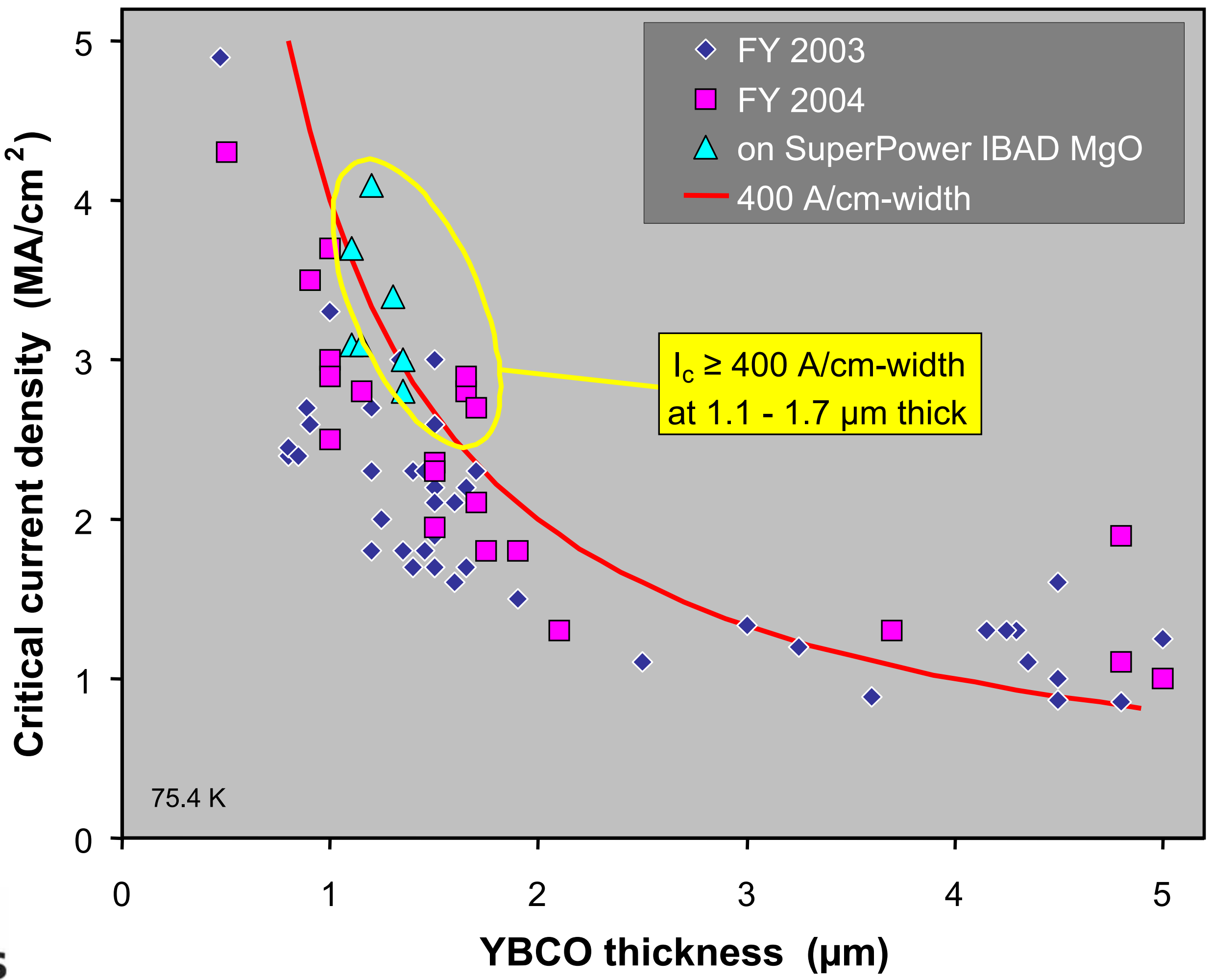
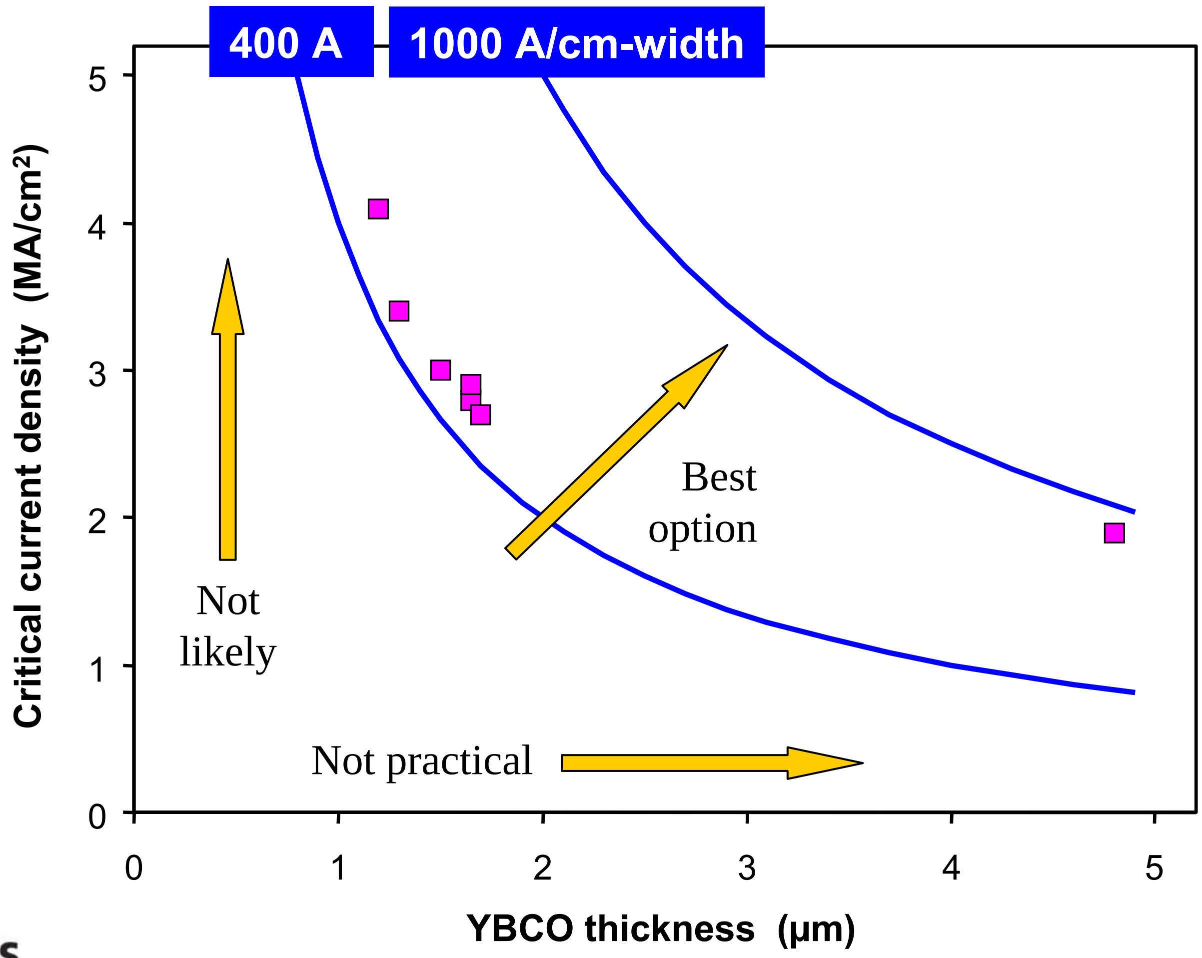
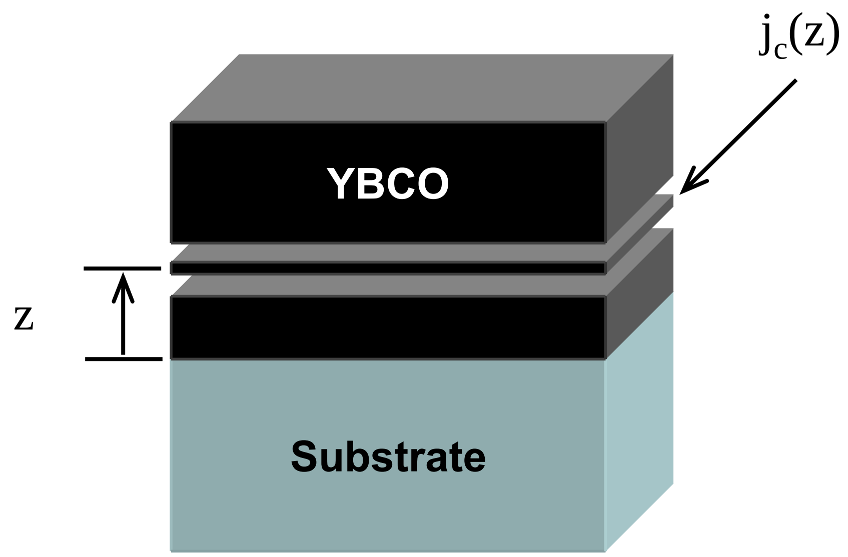
Optimization of the $SrTiO_3$ buffer layer has allowed us to reach our goal of 400 A/cm-width @ 1.5 μm on IBAD MgO



Although optimization delivered incremental improvement a different approach is needed to reach higher current levels.



Our effort to reach higher currents started with consideration of the *incremental* critical current density

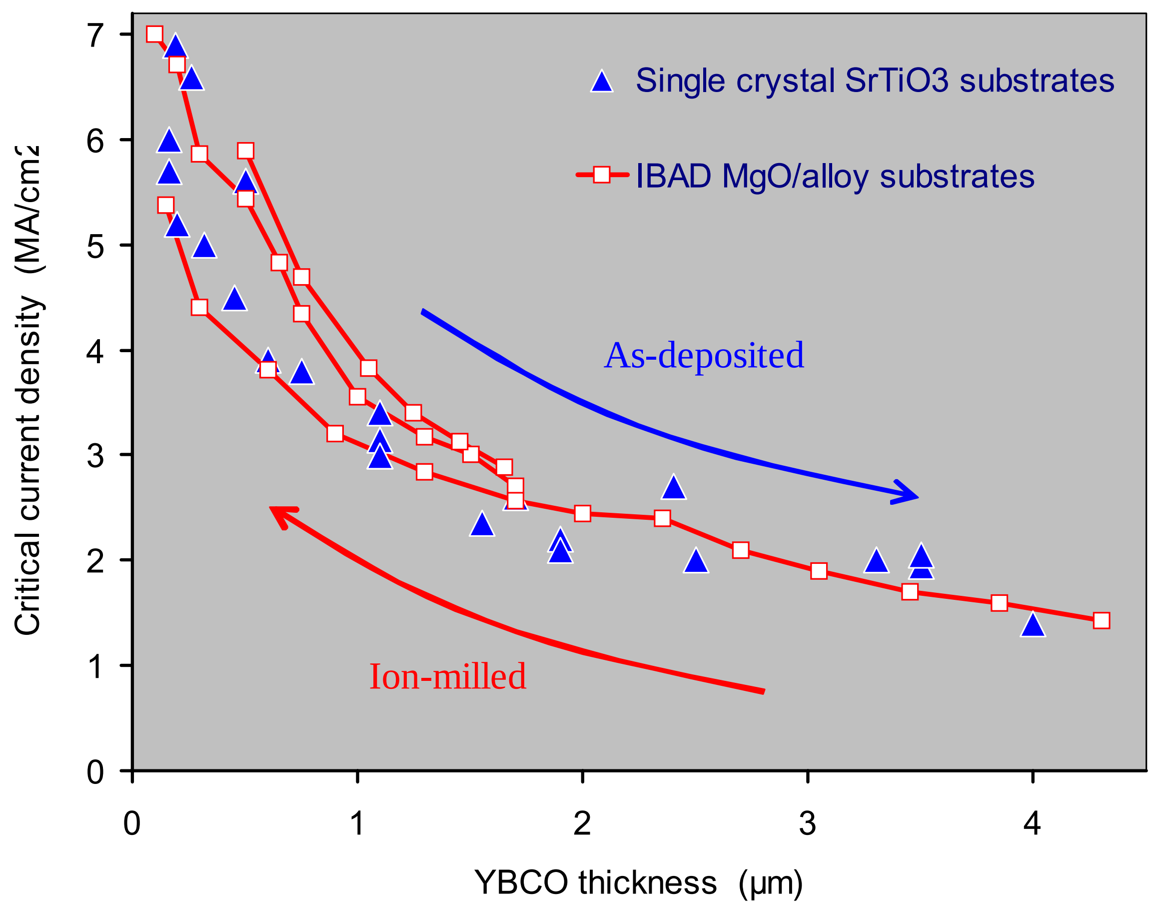


The incremental j_c is the critical current density for a slice of YBCO that has been hypothetically isolated from the rest of the coating and measured.

For PLD YBCO the incremental j_c is established during film growth and is independent of total thickness

Trend is the same whether YBCO is being added or removed.

(These results also demonstrate the equivalence of J_c for IBAD MgO and single-crystal substrates.)



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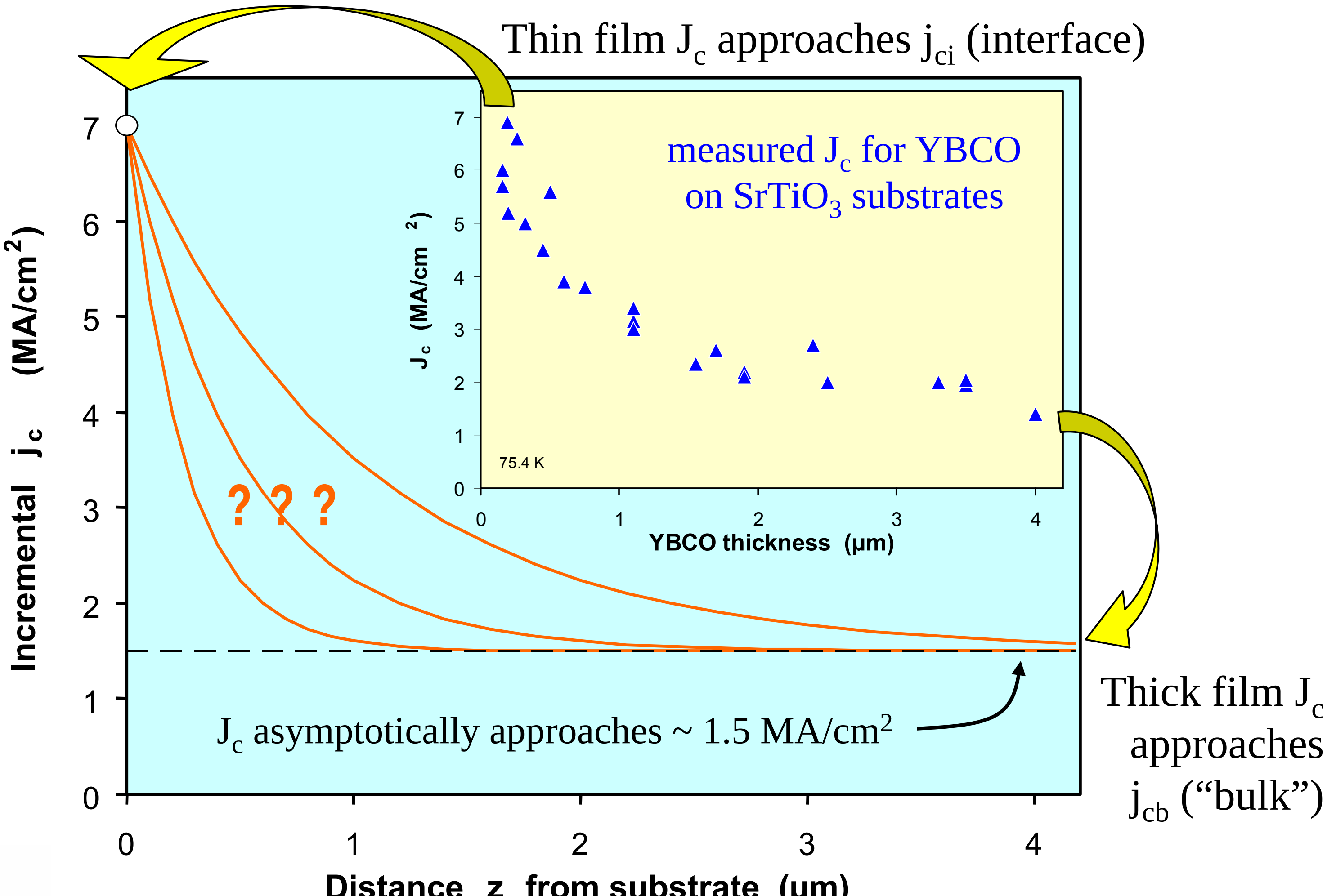
There are two characteristic j_c values for YBCO films that can be estimated from $J_c(t)$ plots



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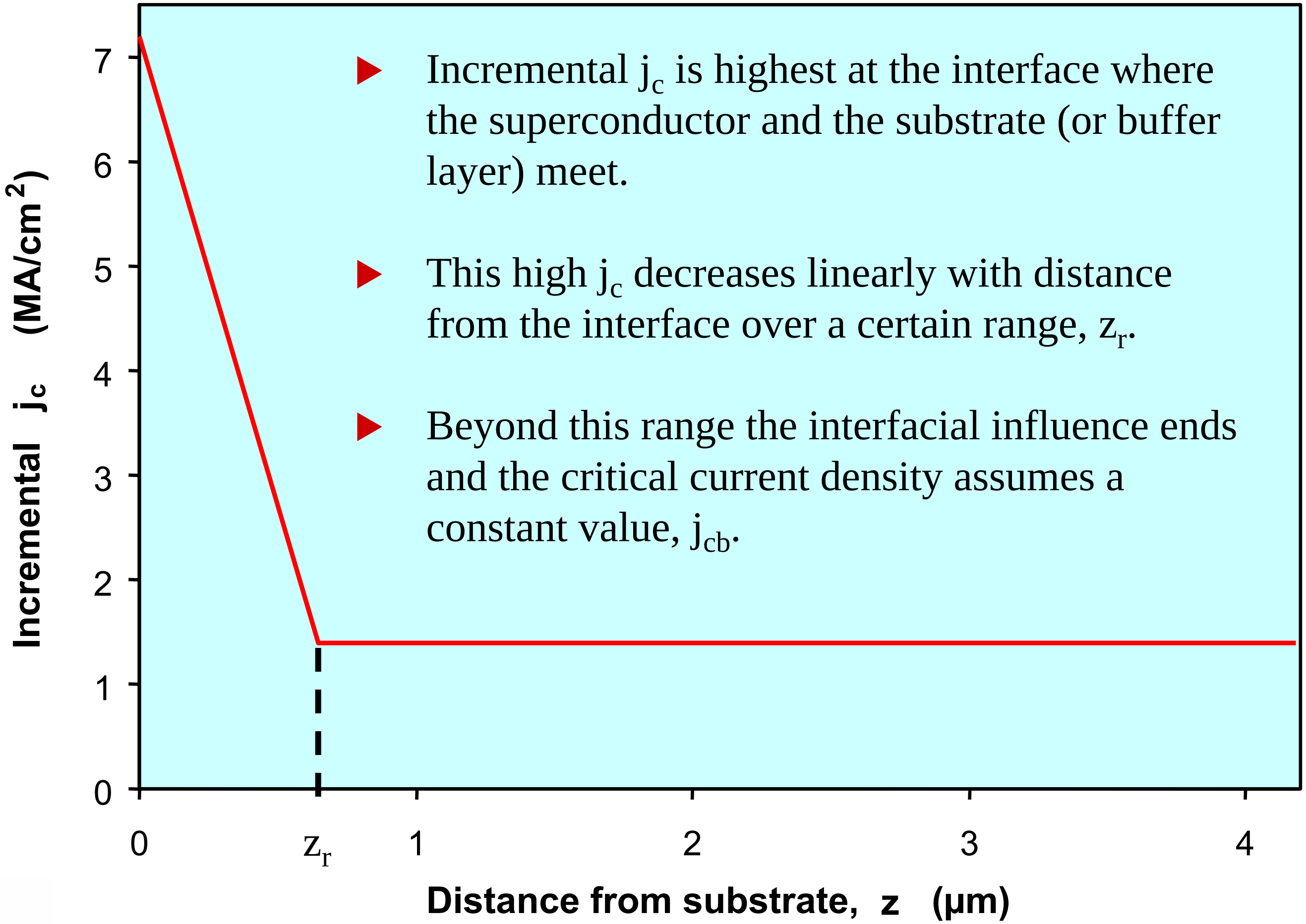
We began with the simplest possible $j_c(z)$ dependence …



- Incremental j_c is highest at the interface where the superconductor and the substrate (or buffer layer) meet.
- This high j_c decreases linearly with distance from the interface over a certain range, z_r.
- Beyond this range the interfacial influence ends and the critical current density assumes a constant value, j_{cb}.

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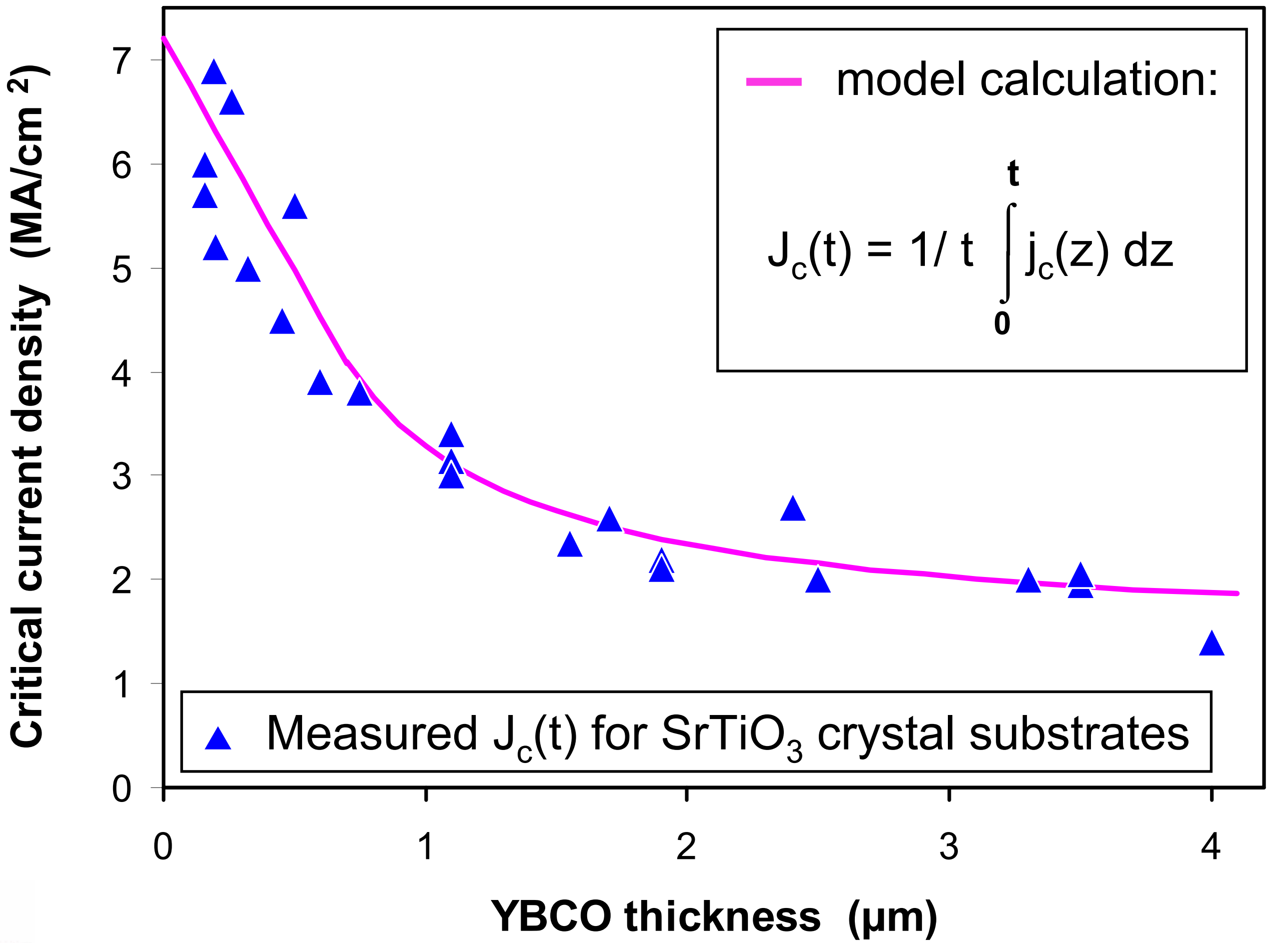
… and found that this dependence gives excellent agreement with measured J_c values



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A possible explanation for the inherent or "bulk" j_c for YBCO comes from recent work by B. Dam *et al.*

- Observed a high density of dislocations between 2D growth islands in PLD films.
- Dislocations are parallel to the c-axis and extend from near the substrate to the film surface.
- Density of dislocations is independent of YBCO thickness.

B. Dam, *et al.*, Phys. Rev. B **65**, 064528 (2002).

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The same work may provide a clue as to the source of high interfacial j_c

- The process that produces threading dislocations also produces misfit dislocations.
- These dislocations only populate the region near the interface.
- Although misfit dislocations lie mainly in the YBCO a-b plane, they create a cross-hatch pattern that may be effective at pinning flux perpendicular to the plane. (H. Safar, *et al.*, Appl. Phys. Lett. **68**, 1853 (1996)).

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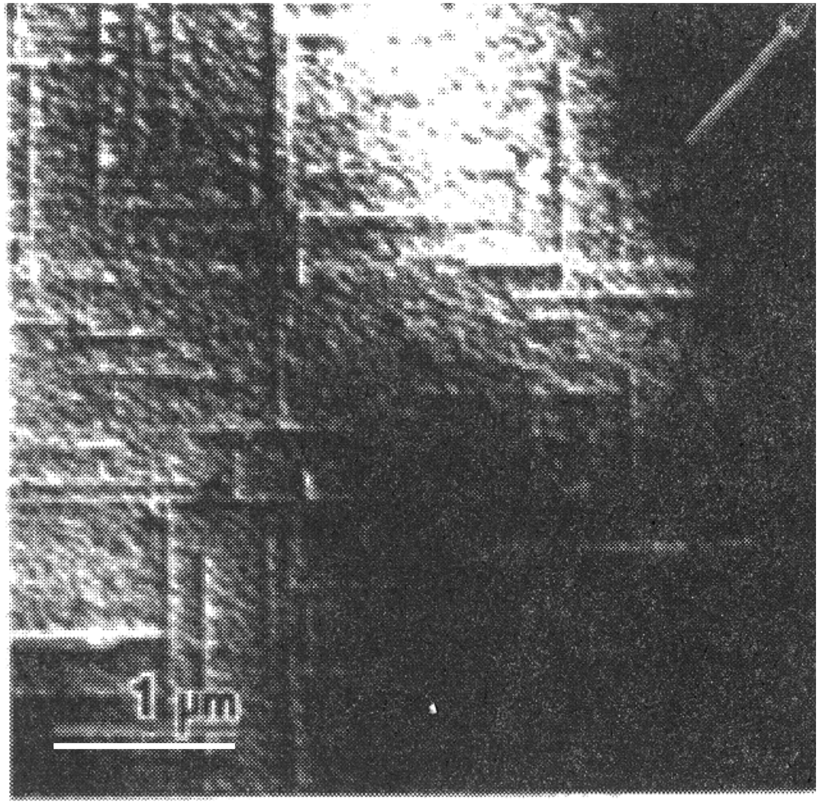
Misfit dislocations are a common feature in heteroepitaxial film growth

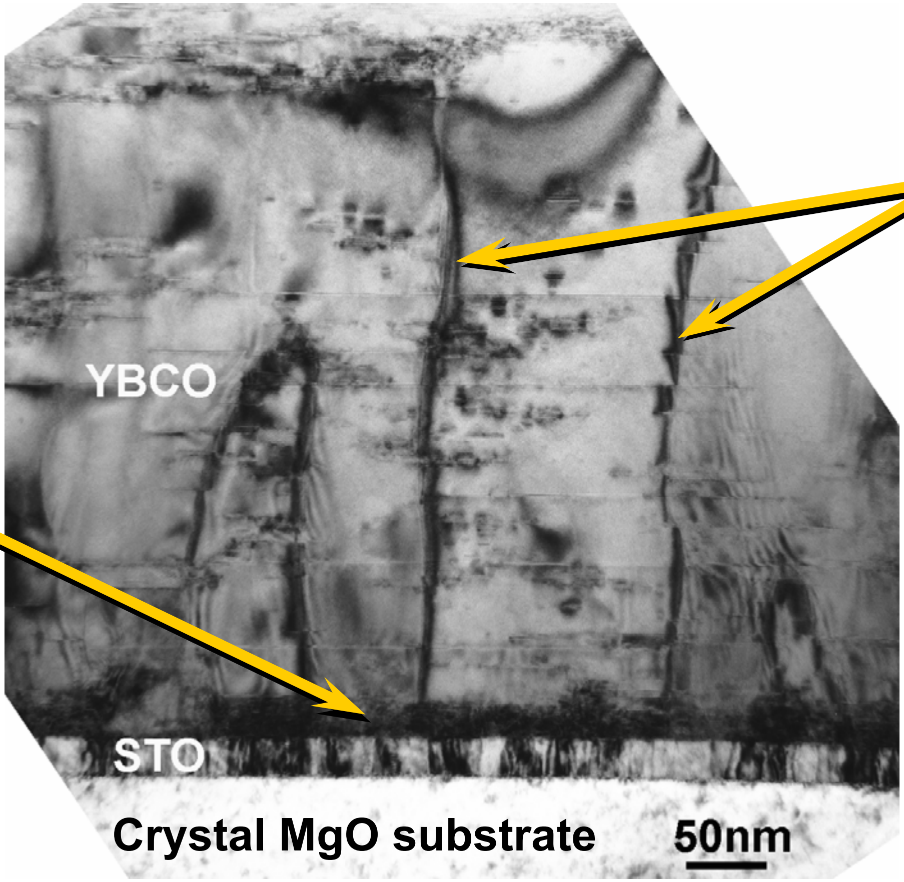


TEM plan view of misfit dislocations in a thin GeSi film on a (001) Si substrate.

J. Washburn, *et al.*, J. Electronic Mat. **20**, 155 (1991).

TEM cross section provides evidence for a high interfacial defect density

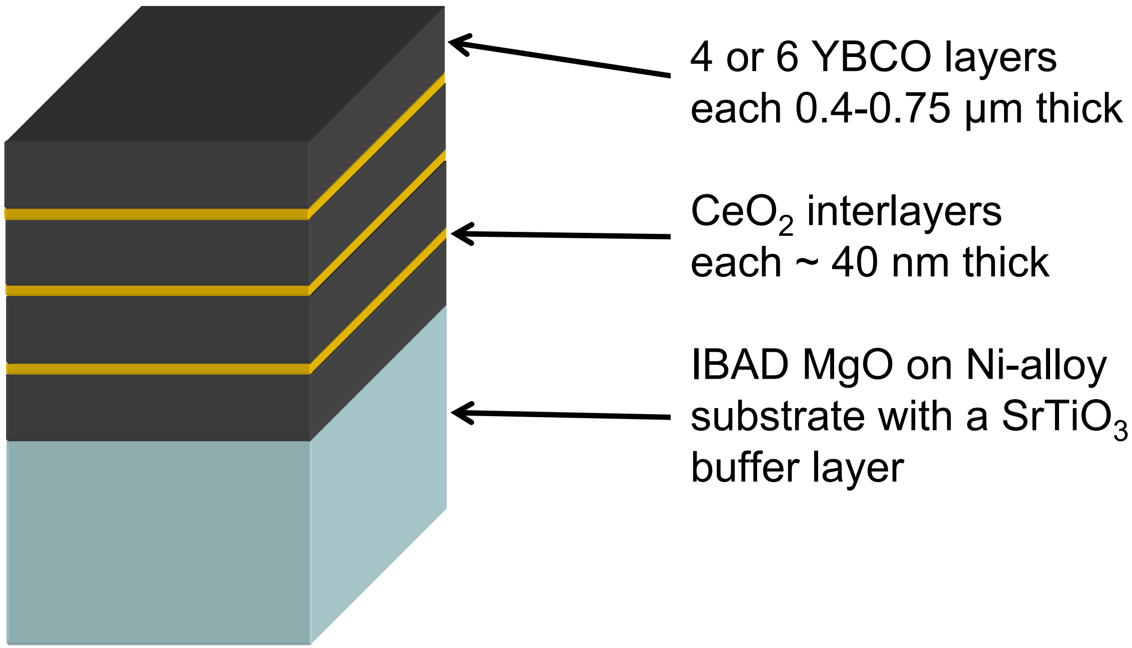
A 20 nm-thick region at the YBCO-$SrTiO_3$ interface with a high density of defects



Threading dislocations between columns

Regardless of the source of high interfacial j_c the model predicts that extra interfaces will increase the average J_c of YBCO

To test: Introduce extra heteroepitaxial interfaces using a YBCO $(CeO_2/YBCO)^n$ multilayer design.

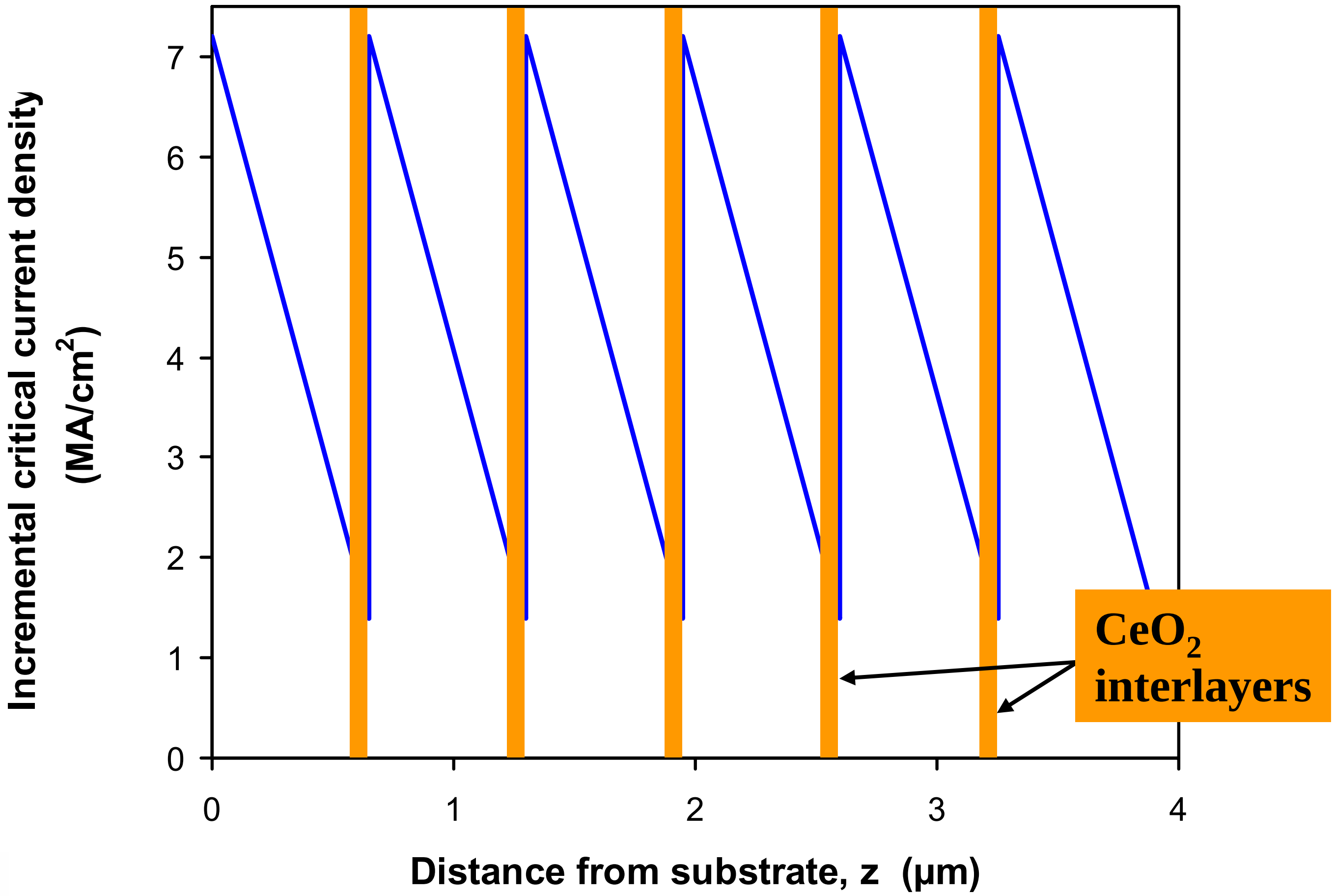


The present work differs from our earlier multilayer work in both design and purpose

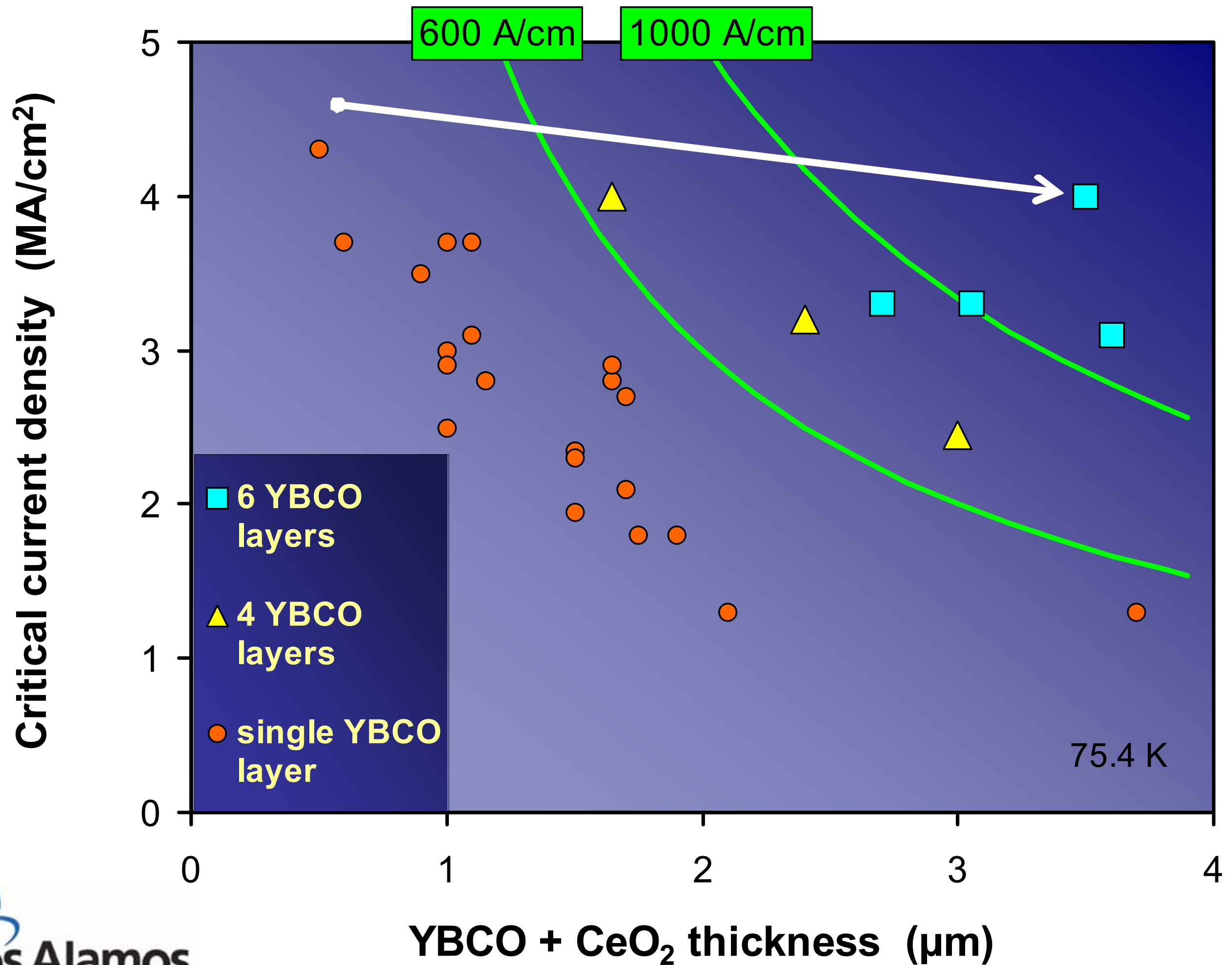
- Earlier work* used multilayers to solve a porosity problem in films more than 1.5 μm thick. Initially CeO_2 interlayers were used, but we quickly switched to Sm 123.
- The porosity problem was ultimately solved by using smoother substrates (presented last year).
- In the present work the CeO_2 interlayers are thinner than before, allowing for electrical contact between YBCO layers.
- Each YBCO layer is thinner and therefore has higher J_c.
- The purpose is to raise J_c by imparting the high interfacial performance to a greater volume of the film.

* Q. X. Jia, *et al.*, Appl. Phys. Lett. **80**, 1601 (2002).

The multilayer philosophy is to create multiple regions of high interfacial J_c throughout the coating



The YBCO/CeO_2 multilayer approach significantly increases thick-film J_c and enables achievement of I_c levels above 1000 A/cm-width



Arrow:

Expected J_c for 0.58 μm single layer is 4.6 MA/cm^2.

Measured J_c for 3.5 μm multilayer (six 0.58 μm YBCO layers) is 4.0 MA/cm^2.

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Scoring criterion – Results

1. Damage anisotropy experiments provided the first confirmation of IBAD MgO texturing mechanism.

2. Established a methodology to quantitatively determine impurity concentrations in YBCO films and measure the effect of substrate elements on superconducting properties.

3. For the first time measured diffusion coefficients of transition metal elements in alumina films, as used in our IBAD MgO architecture.

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Scoring criterion – Results (continued)

4. Produced many films on IBAD MgO in the 1.1-1.7 μm thickness range with I_c > 400 A/cm-width.

5. Took a fresh look at the J_c drop with YBCO thickness and significantly improved upon the situation by using YBCO-CeO_2 multilayers.

6. Highest current on IBAD MgO in 2003:
   720 A/cm-width at 4.5 μm.
   Highest multilayer currents on IBAD MgO in 2004:
   660 A/cm-width at 1.65 μm
   1000-1400 A/cm-width at 3.1-3.6 μm.

Scoring criterion – Performance

- Experimentally investigate the fundamental texturing mechanisms of IBAD. *Goal: Develop a model that will allow us to further refine IBAD deposition parameters and texture.*

- Determined that damage induced by Ar ion irradiation of MgO exhibited an anisotropy that conformed to: $\chi_{max}^{(110)} < \chi_{max}^{(100)} < \chi_{max}^{(111)}$.

- Temperature dependent damage accumulation data implied that IBAD texturing would improve at low temperatures.

- Although optimum texturing was unchanged at low temperatures, the processing window was expanded.

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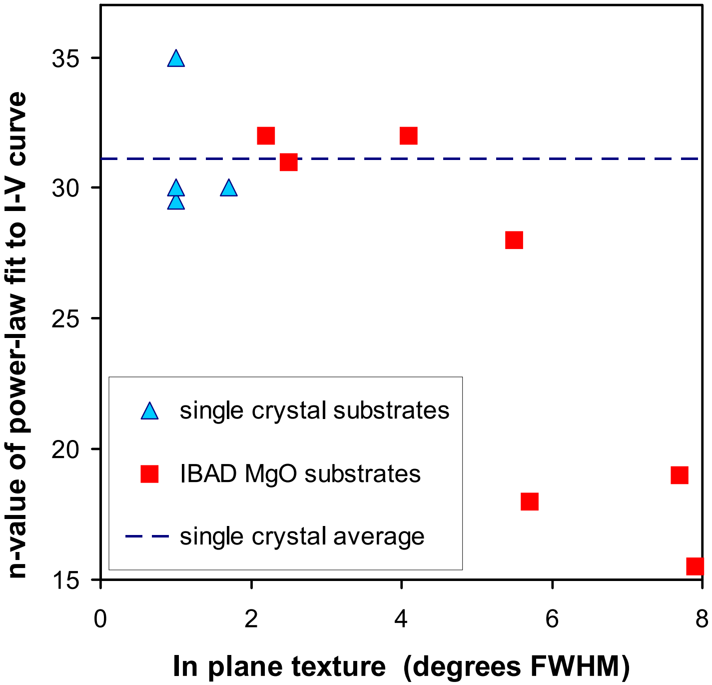
Scoring criterion – Performance

- Use extended I-V curves for IBAD MgO to evaluate the validity of the bicrystal plateau analogy for coated conductors. *Goal: Determine whether improved texture will yield higher J_cs.*

- Extended I-V curves proved to be less sensitive for IBAD than for bicrystals because of the large number of grain boundaries in the current path.
- However, the n-value (as in $V = I^n$) is a good indicator of the transition to weak-link behavior at 4-5° FWHM.



Scoring criterion – Performance

- Approach the drop in J_c with thickness as though it is a materials-processing issue, and not intrinsic. At a particular thickness, maximize J_c through a comprehensive process optimization. *Goal: Reproducible achievement of I_cs over 400 A/cm-width at a film thickness of ≤ 1.5 μm.*

- Met this goal by optimizing the $SrTiO_3$ buffer layer; however, J_c at 1.5 μm is still significantly less than that for very thin films.

- Took a fresh look at the thickness dependence of J_c and concluded that extra interfaces inside the YBCO would be beneficial.

- Created extra interfaces using a multilayer design and reproducibly achieved the world's first I_c levels greater than 1000 A/cm-width (75.5 K).

Scoring criterion – Performance

- Design and implement systematic experiments to determine if chemical modifications to REBCO offer enhanced performance, particularly in an external magnetic field. *Goal: Reproducibly double J_c at 75 K in a magnetic field parallel to the c-axis.*

- This goal was met using two different approaches.
- One approach was the addition of $BaZrO_3$ to the PLD target, resulting in flux-pinning BZO nanoparticles in the films.
- A second approach resulted from a systematic study of mixed-rare-earth 123 compounds.
- See talk by Judith Driscoll and Leonardo Civale tomorrow in this session for details.

Scoring criterion – Performance

- Use ion-milling and SIMS to determine the quantitative tolerance of YBCO to diffusing substrate materials, and use this information to minimize the nonsuperconducting layer thickness. *Goal: < 100 nm.*

- Established a sound methodology, consisting of three parts to address this goal.

1. Developed a way to produce films with controllable impurity concentrations.

2. Selected Particle-Induced-X-ray-Emission (PIXE) to measure impurity concentrations. Measured concentrations of Ni in YBCO.

3. Used ion milling to test whether diffusion was a problem when very thin $SrTiO_3$ was used.

Scoring criterion – Performance

- Develop a single material that can serve as both a barrier and nucleation layer. *Goal: Reduce the number of layers by one, and reduce the barrier/nucleation layer thickness by 20 nm, with no reduction in performance.*

- Found a candidate that functions as both barrier and nucleation layer: Er_2O_3.
- However, we postponed this task while working to establish the means of quantitatively evaluating barrier properties of films (previous goal).
- We will consult with our industrial partners before continuing this task to determine their level of interest in a single barrier/nucleation layer.

Scoring criterion – Performance

- Continue using our 1 meter tape capability to supply IBAD MgO to industrial partners and other national laboratories, and work with them individually to achieve optimum YBCO performance. *Goal: Three organizations depositing YBCO with J_cs equivalent to those on single-crystal substrates.*

- During the year SuperPower developed its own capability to continuously process high-quality IBAD MgO, and AMSC received lengths from the Research Park. These developments negated the need for the Core Program to supply lengths to partners.

- Single crystal equivalent J_cs were reached with our PLD YBCO on SuperPower's IBAD MgO → 300-400 A/cm-width @ 1.2-1.5 μm thick.

Scoring criterion – Research integration

- Our primary research integration activity this year was the transfer of IBAD MgO technology to SuperPower. This was accomplished by sample and information exchanges, equipment loans, and site visits.

- The result of this activity is that SuperPower (SP) has successfully implemented their own IBAD MgO capability in a very short time. Highlights:

- SP IBAD/LANL buffers & YBCO → 2.8-4.1 MA/cm^2 @ ~ 1.2 μm YBCO

- SP IBAD & buffers/LANL YBCO → 2.3 MA/cm^2 @ 1.5 μm YBCO

- SP continuous process (MOCVD YBCO) → 1.9 meters, 116 A.

- SP IBAD MgO → 50 meters, ~ 6° FWHM, 10 meters/hour

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Scoring criterion – FY2005 plans

Consult with our industrial partners to address strategies of mutual interest for increasing performance and reducing costs.

- Modify IBAD assist gun to expand deposition zone length to improve process efficiency. *Goal: Double window to 90% of gun length.*

- Improve IBAD MgO texture by reducing divergence of SuperPower's ion-assist gun. *Goal: Routinely obtain* $\Delta\Phi \leq 5°$ *FWHM.*

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Scoring criterion – FY2005 plans (continued)

- Expand upon our data of how YBCO superconducting properties (T_c, J_c) are affected by transition metal impurities. *Goal: Determine tolerance limits for substrate elements in YBCO films.*

- Continue to refine multilayers to exploit very high J_cs for thinner YBCO. *Goals: Reproducible 1000 A/cm-width in 2.5 μm. Assist industrial partners in implementing multilayer designs appropriate to their deposition technologies.*

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